

# AIR TRAFFIC MANAGEMENT AS PRINCIPLED NEGOTIATION BETWEEN INTELLIGENT AGENTS

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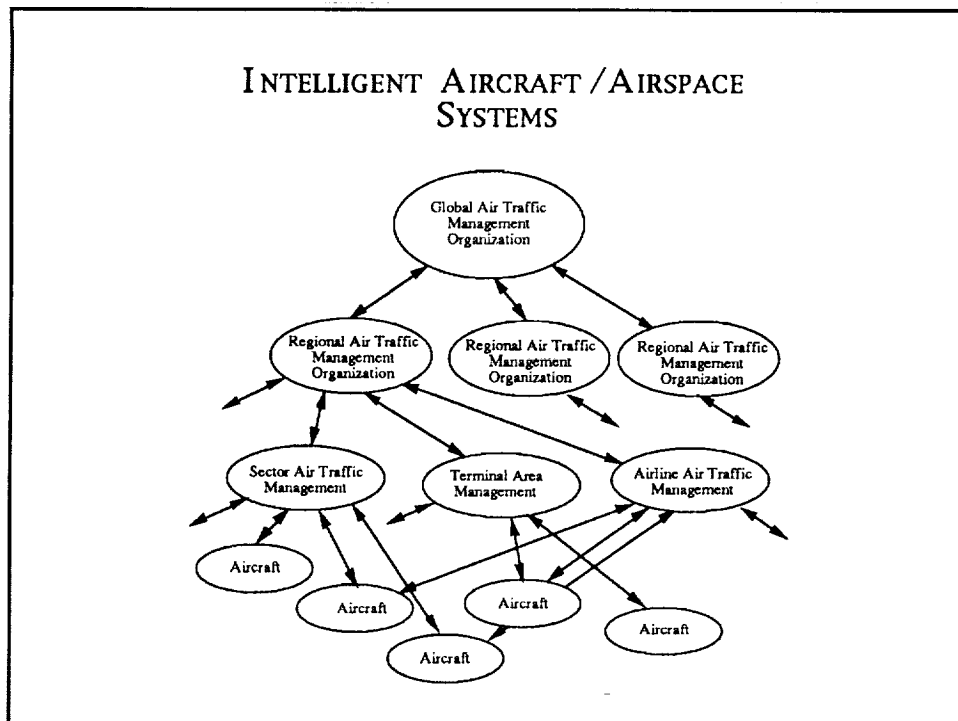
The major challenge facing the world's aircraft/airspace system (AAS) today is the need to provide increased capacity, whilst reducing delays, increasing the efficiency of flight operations, and improving safety. Technologies are emerging that should improve the performance of the system, but which could also introduce uncertainty, disputes, and inefficiency if not properly implemented.

The aim of our research is to apply techniques from intelligent control theory and decision-making theory to define an Intelligent Aircraft/Airspace System (IAAS) for the year 2025. The IAAS would make effective use of the technical capabilities of all parts of the system to meet the demand for increased capacity with improved performance.

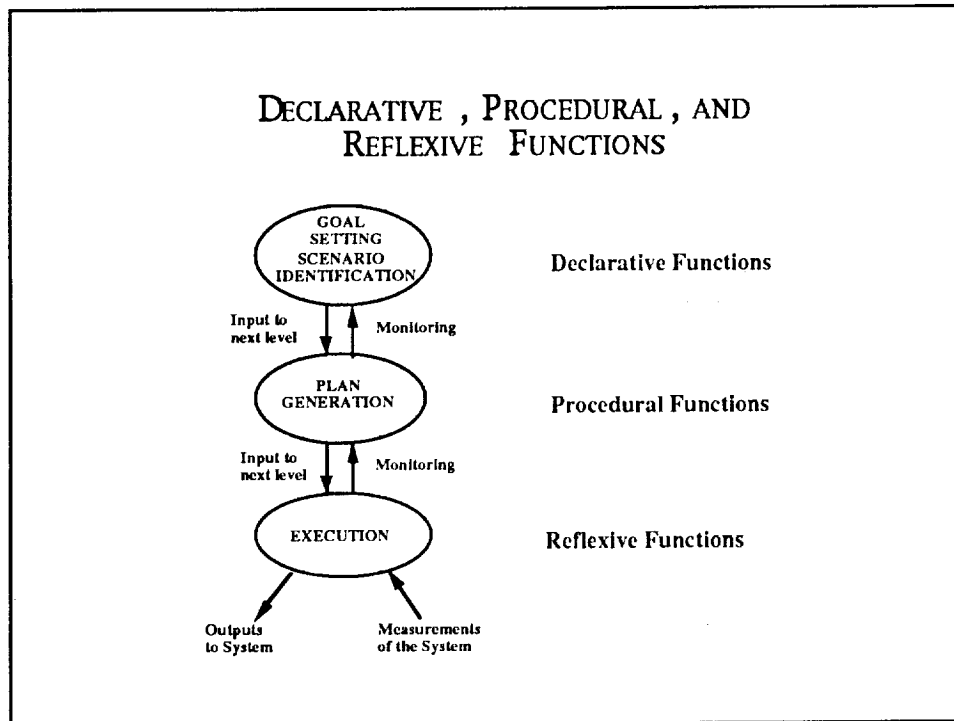
An Intelligent Aircraft Airspace System (IAAS) would allow each of these agents to interact in a way that:

- makes full use of the differing capabilities of all the agents
- allows each agent to obtain data residing in other parts of the system
- imposes as few restrictions as possible on aircraft operations in order to meet system performance requirements
- provides system robustness through dissimilar redundancy
- allows graceful degradation of system performance if any part should fail.

The Aircraft Airspace System consists of a variety of agents, operating in a broadly hierarchical structure. At the lowest level are the individual aircraft, from general aviation to commercial traffic; at the highest level are global organizations such as ICAO. At intermediate levels not only are there the various parts of today's air traffic management system, such as sector air traffic management (ARTCCs in the US), but also the airlines who already cooperate with flow control, and provide an increasingly important role in supporting aircraft in flight.



Each agent in the system is itself intelligent; it does more than execute instructions generated by the superior agent in the hierarchy. An Intelligent Agent performs a hierarchy of functions, bounded on one end by declarative functions, which typically involve decision-making, and on the other by reflexive functions, which are more-or-less spontaneous reactions to external or internal stimuli. An intermediate level, procedural functions, may also be defined. Like reflexive functions, these have a well-defined input-output characteristic, but have a more complicated structure.



This model of an intelligent agent can be used to describe any of the agents within the IAAS. Intelligent agent descriptions of a traffic control agent and a pilot/aircraft agent are given for illustration. The effect of emerging technologies will be to enhance the capabilities of the agents in all these functions. This will increase the overlap in capabilities of the agents.

As an example, collision avoidance systems (CAS) provide the pilot/aircraft agent with traffic situation data, previously only available to traffic control agents. These systems should provide increased safety, but have also on occasions caused conflict, when the CAS has issued instructions that conflicted with what the traffic control agent had planned.

The IAAS must be able to overcome these types of potential problems, while exploiting the possibilities provided by the enhanced and overlapping capabilities of the agents.

## FUNCTIONS OF INTELLIGENT AGENTS IN IAAS

### TRAFFIC CONTROL AGENT

#### Declarative Functions

Sector allocation  
Traffic monitoring  
Conflict detection/prediction  
Constraint monitoring  
Hazard detection  
Route assignment

#### Procedural Functions

Conflict resolution  
Flight path adaptation  
Networking  
Assessment of pilot requests  
Flow control

#### Reflexive Functions

Display update  
Communications  
State vector processing  
Aircraft handover

### PILOT/AIRCRAFT AGENT

#### Declarative Functions

System monitoring  
Goal planning  
System/scenario identification  
Choice of operating mode

#### Procedural Functions

Adaptation  
Guidance  
Navigation  
Crew coordination  
Networking

#### Reflexive Functions

Measurement  
State Estimation  
Control  
Communication

Each agent, either through its own sensors or through communications, will have the data and the computational ability to carry out strategic functions such as flight path modification, taking into account the interests of other agents as well as its own. By Inventing Options for Mutual Gain, and Assessing Options using Objective Criteria, agreements should be reached that benefit both parties. If more of the agents' interests are satisfied, the system is performing better.

Principled Negotiation is proposed as the structure for interaction of agents in the IAAS. Air traffic management can be viewed as a negotiation process; as the agents interact each is trying to best satisfy their own interests. Principled Negotiation exploits the fact that two parties in negotiation will have common interests on which an agreement that benefits both parties can be reached. Each agent in the IAAS has a different set of interests, but many interests are held in common.

### PRINCIPLED NEGOTIATION

- Identify Common and Separate Interests
- Invent Options for Mutual Gain
- Assess Options using Objective Criteria

Fisher, R., Ury, W., *Getting to Yes*, Penguin Books, New York, 1981

**Aim:**

Use Principled Negotiation to allow agents in the IAAS to effectively interact, and so improve system performance.

**Why:**

- Proliferation of sources and quantity of data available to each agent
- Principled Negotiation allows each agent to contribute according to its capabilities

Negotiation is a viable model for cooperative decision-making in the IAAS, because of the large areas of common interest between the agents. Given a set of alternative decisions, two agents may often regard different decisions as optimal, because each agent will weight each factor differently. However it should be possible for the two agents to identify a single decision that, though not ideal for both agents, does better meet the interests of both agents than the status quo. Principled Negotiation provides a method by which this beneficial agreement can be achieved effectively.

#### EXAMPLES OF COMMON AND SEPARATE INTERESTS

	Pilot/ Aircraft	En-route Controller	Airline	Airport Operator
Safety	✓	✓	✓	✓
Fuel Costs	✓		✓	(✓)
Delays	✓	✓	✓	
Profit	(✓)		✓	✓
Throughput		✓	(✓)	✓
Scheduling Freedom			✓	

Each agent regularly searches for Options for Mutual Gain. It should consider the interests of the other agents in the system, not just its own. If a pilot/aircraft agent is searching for possible improvements to its flight path, it will be able to draw on data that describes the local traffic and weather situation, and may well have access to data on sectors further into the flight path, as well as the predicted situation at the destination airport at its planned arrival time. In assessing various options it should consider not only its own interests (fuel usage, time of arrival etc.), but also the interests of other agents. Does the option reduce traffic in an overloaded sector? Would arrival at the airport at a different time reduce a predicted peak in runway demand?

Once an agent has generated an option that provided mutual benefit, it would propose the option to the superior agent in the hierarchy. In the case of a proposed change in the flight path this would be the traffic control agent. The superior agent should assess any proposal using objective criteria. In the IAAS, objective assessment of a proposed flight path change would involve not only local analysis, but assessment of the impact of the change over as long a time scale and as wide a geographical area as possible.

### INVENT OPTIONS FOR MUTUAL GAIN

*Each agent regularly searches for options of benefit to itself and other agents*

#### Example:

- Aircraft obtains traffic, weather, destination airport data from
  - ground control
  - aircraft sensors
  - communications with other aircraft
- Aircraft uses data to search for changes to flight path that will:
  - save fuel
  - minimize delay
  - improve traffic situation for ATC
  - improve traffic flow at destination
- Aircraft assesses options, and enters negotiation with ATC

### ASSESS OPTIONS USING OBJECTIVE CRITERIA

*Options assessed by each agent on the basis of objective criteria*

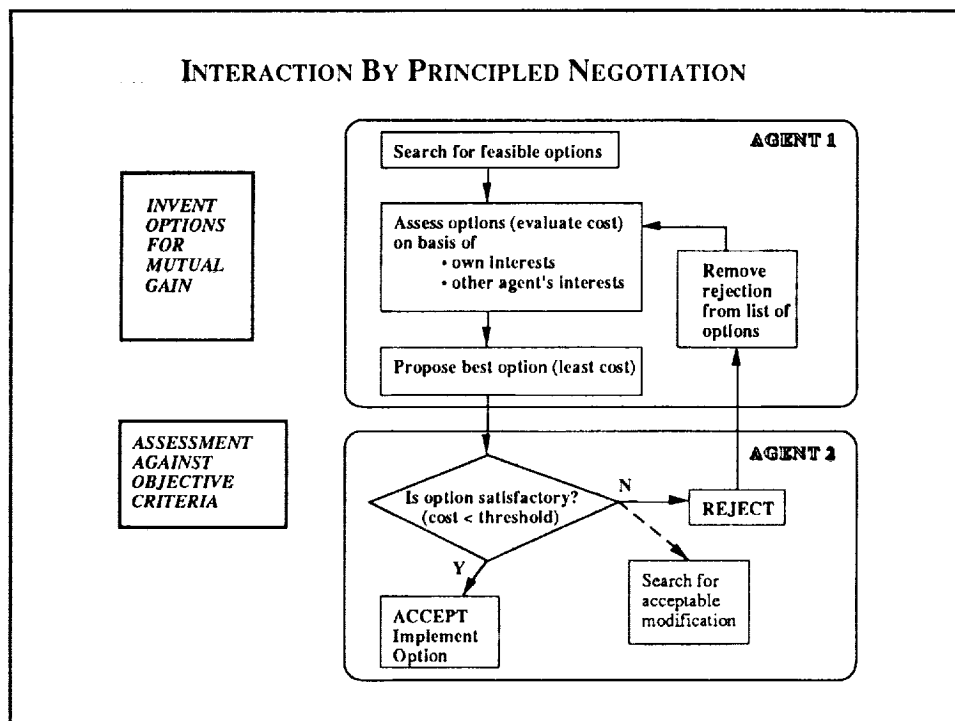
#### Examples of objective criteria:

- Effect on safety
  - probability of conflict
  - mean separation, min. separation
  - weather hazard avoidance
- Effect on system performance
  - average flight delay
  - sector throughput
  - airport throughput
  - minimized flight time
- Effect on direct and indirect costs

*Each agent assesses options using criteria that reflect its own and other agents' interests*

The assessment of flight path changes is just one example of the many tasks that are undertaken in the IAAS. Most of these tasks involve the interaction of two or more agents, and Principled Negotiation should be applicable in all cases. These could be tasks occurring over time scales of months or years (such as airport slot allocation, or flight scheduling) or over short time scales (such as scheduling inbound streams of traffic in a terminal area).

This slide shows an algorithm that could be applied in any of these cases. Agent 1 would regularly conduct a search for options that provided mutual benefit. That benefit would probably be on the basis of a cost function that reflected the interests of itself and other agents. The best option would then be proposed to agent 2 (the superior agent). Agent 2 would make its own evaluation of the cost of the option, using its own data and possibly a different cost function. Different criteria could be used for accepting a proposal; one might be to accept a proposal if its cost was below a certain threshold. If the option was unacceptable, agent 2 might propose a modification to agent 1, or agent 1 might suggest an alternative.





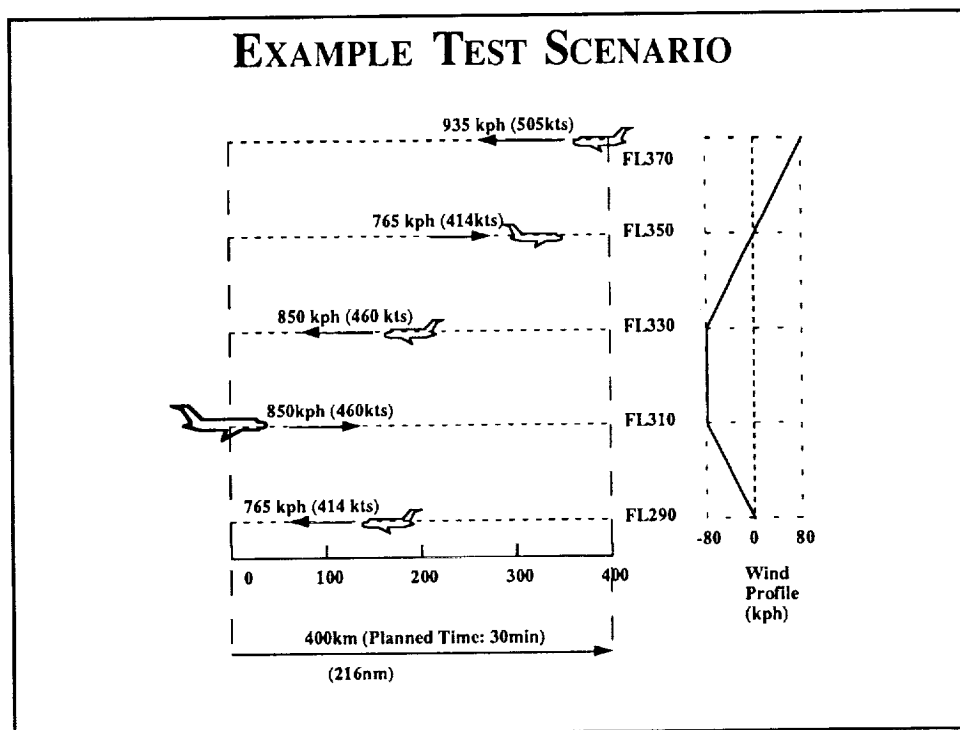
Current research is focussed on applying these ideas to a test scenario, and evaluating the concept. The initial test scenario is a 2D high level (FL290 - 370) sector. Although superficially a simple scenario, it provides a rich set of variables which can be analyzed. Some examples of effects which can be studied are:

- effect of different agent cost functions
- effect of conflicting aircraft data
- effect of wind distributions and other weather phenomena
- effect of different negotiation algorithms.

The decision-making system can be tested on various traffic distributions, and the effectiveness of the system analyzed in terms of:

- safety
- efficiency of operations
- capacity of the system
- punctuality (accuracy of aircraft at 4D waypoints)

This scenario mainly deals with pilot/aircraft - traffic control agent interactions. The scenario can easily be made more complex, and eventually it is hoped to examine the possibilities of such a system in terminal airspace.



In summary, the capabilities of the agents in a future AAS will overlap to a much greater degree than at present. As each agent becomes increasingly intelligent, the declarative functions of the agents will have increasing commonality. The key to improved performance of a future AAS will be the effective use of these overlapping capabilities.

Overlapping capabilities can provide increased redundancy and flexibility for AAS operations, and effective combination of these overlapping yet distinct capabilities should give an IAAS improved performance compared to today's system. Principled Negotiation is proposed as a form of agent interaction that allows each agent to use its capabilities to ensure that decisions taken better meet each agents interests, and so improve system performance.

Work validating the concept in a 2-D en-route traffic scenario is progressing.

## CONCLUSIONS

- An IAAS consists of a hierarchy of Intelligent Agents
- Each agent described by reflexive, procedural, declarative functions
- Increasing overlap in agent capabilities
- Need for a system that makes effective use of overlapping capabilities for good system performance
- Principled Negotiation proposed as the basis for cooperative decision-making in the IAAS